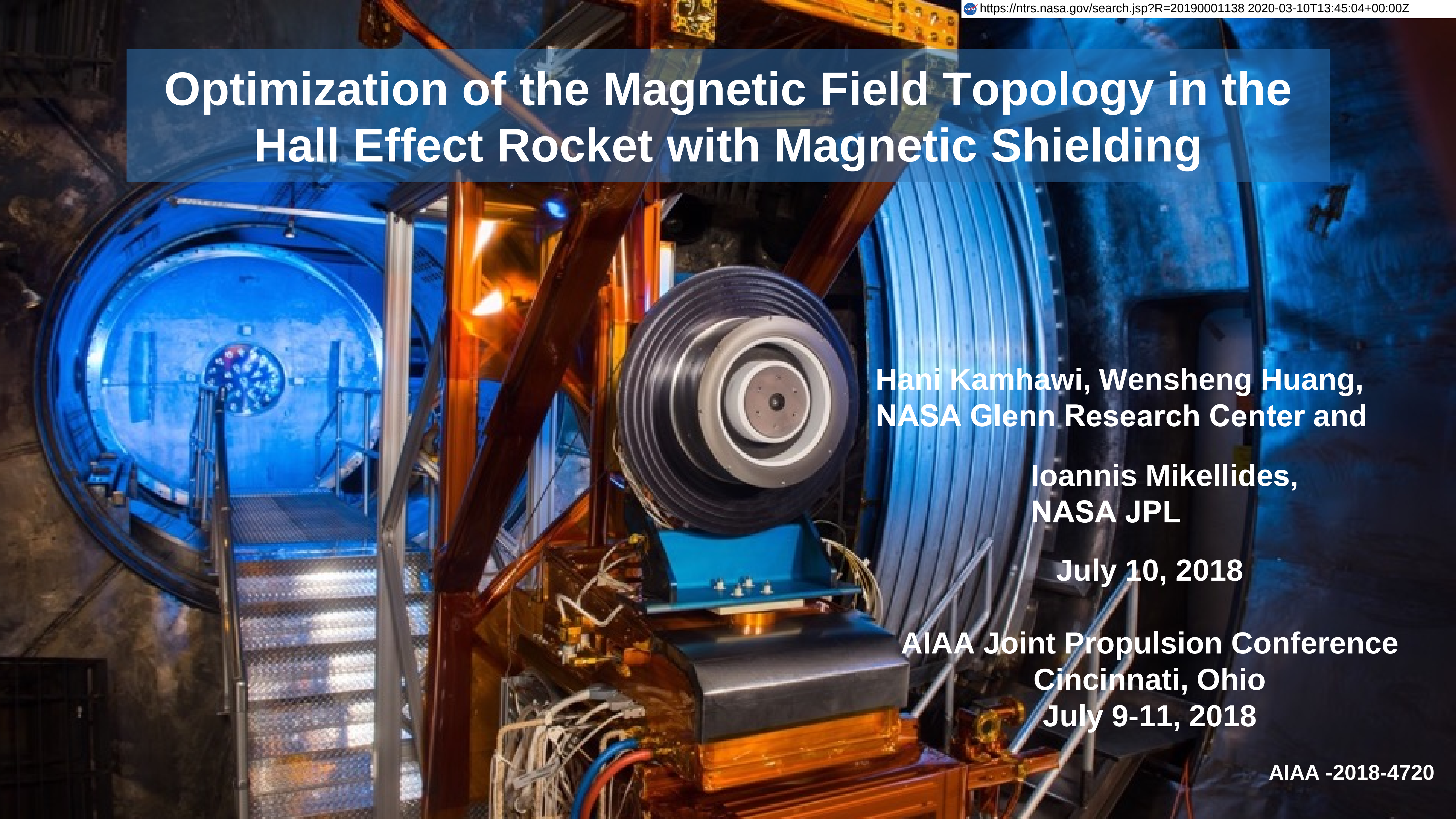

Optimization of the Magnetic Field Topology in the Hall Effect Rocket with Magnetic Shielding

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NASA Glenn Research Center and

Ioannis Mikellides,
NASA JPL

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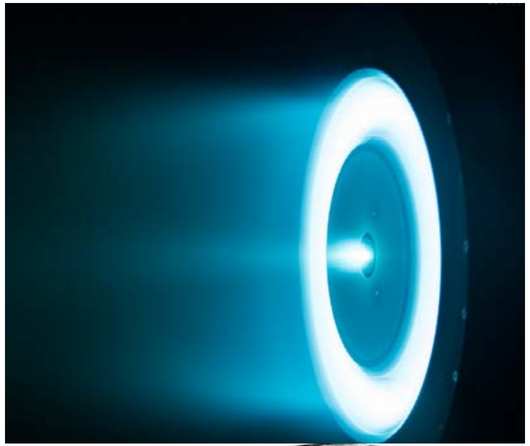
AIAA -2018-4720

Outline

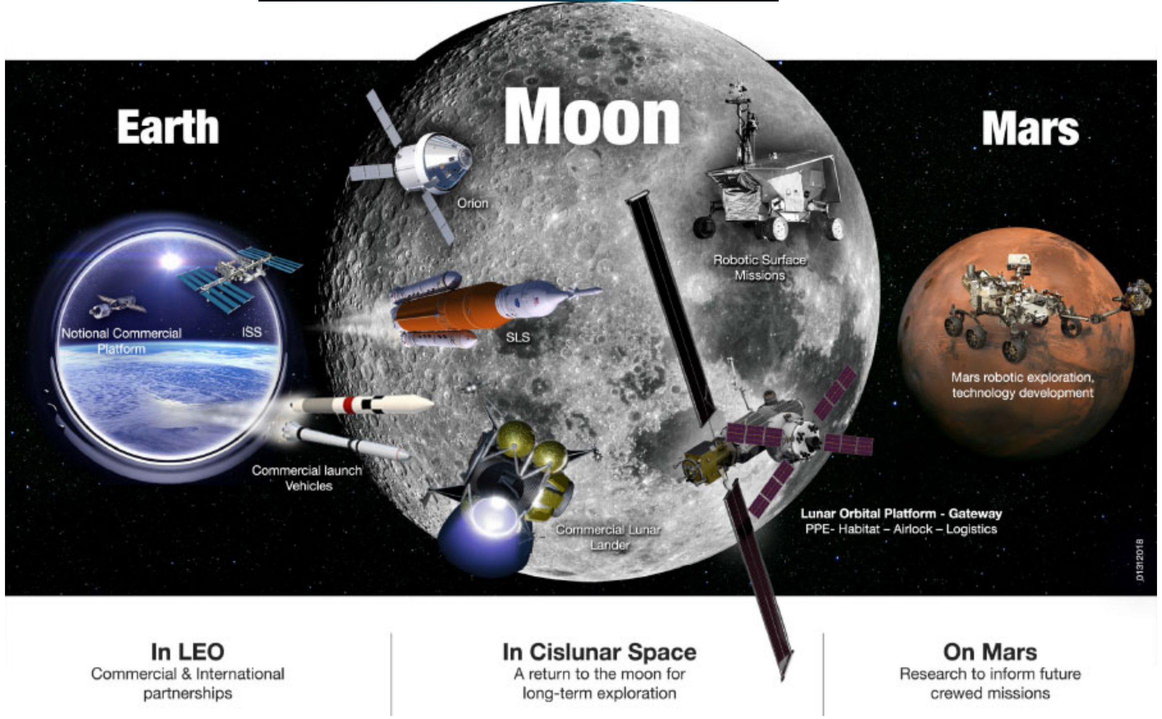
- Introduction
- Background
- Motivation
- Magnetic field topology optimization
- Hall2De modeling and simulation
- Test Plan
- Initial Phase I test results
- Summary

Introduction

- A NASA GRC and JPL team developed a 12.5-kW, magnetically-shielded Hall thruster, called Hall Effect Rocket with Magnetic Shielding (HERMeS)
- In 2016 transitioned to commercial production under Aerojet Rocketdyne’s Advanced Electric Propulsion System (AEPS)
- AEPS candidate to provide propulsion for the Power and Propulsion Element for NASA’s Gateway
- Continuing risk reduction activities using HERMeS

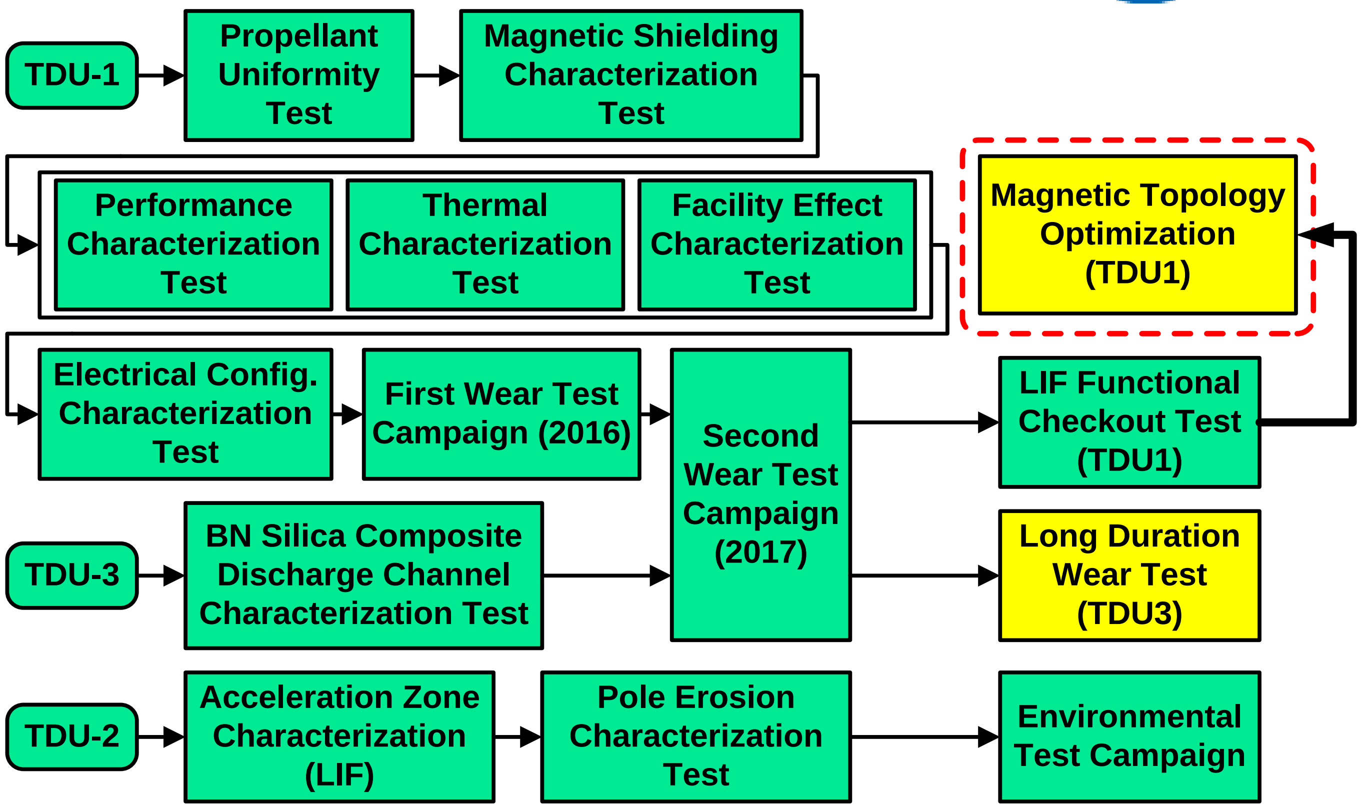


◄ HERMeS in operation



HERMeS Test Campaign Status

- Overview found in IEPC-2017-284 & 231
- Other NASA GRC JPC papers on HERMeS
  - **Frieman et al.**, Long Duration Wear Test of the NASA HERMeS Hall Thruster. **AIAA-4645**
  - **Mackey et al.**, Uncertainty in Inverted Pendulum Thrust Measurements. **AIAA-4516**
  - **Benavides et al.,** Diagnostic for Verifying the Thrust Vector Requirement of the AEPS Hall-Effect Thruster and Comparison to the NEXT-C Thrust Vector Diagnostic. **AIAA-4514**
  - **Ahern et al.,** In-situ Diagnostic for Assessing Hall Thruster Wear. **AIAA-4721, Tue @ 16:00**
  - **Huang et al.,** Ion Velocity in the Discharge Channel and Near-Field of the HERMeS Hall Thruster. **AIAA-4723, Tue @ 17:00**
  - **Hall et al.,** Preparation for Hollow Cathode Testing for the Advanced Electric Propulsion System at NASA Glenn Research Center. **AIAA-4425**



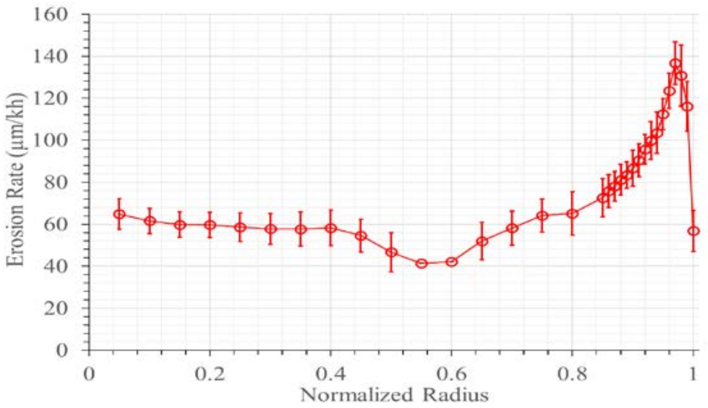
Lobbia et al., AIAA-4646
Lopez-Ortega et al., AIAA-4647
Mikellides et al., AIAA-4722, Tue @ 16:30

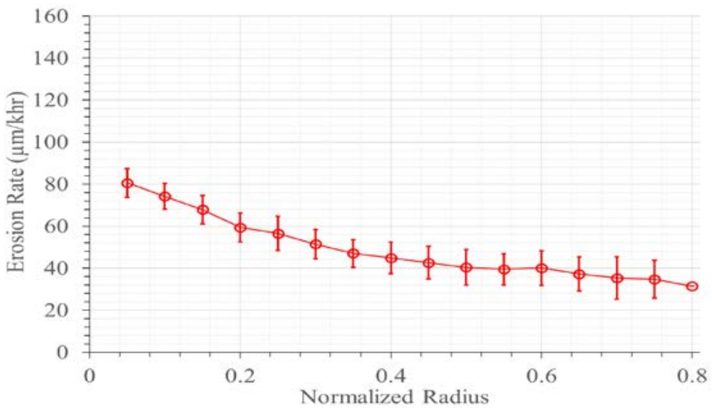
Motivation

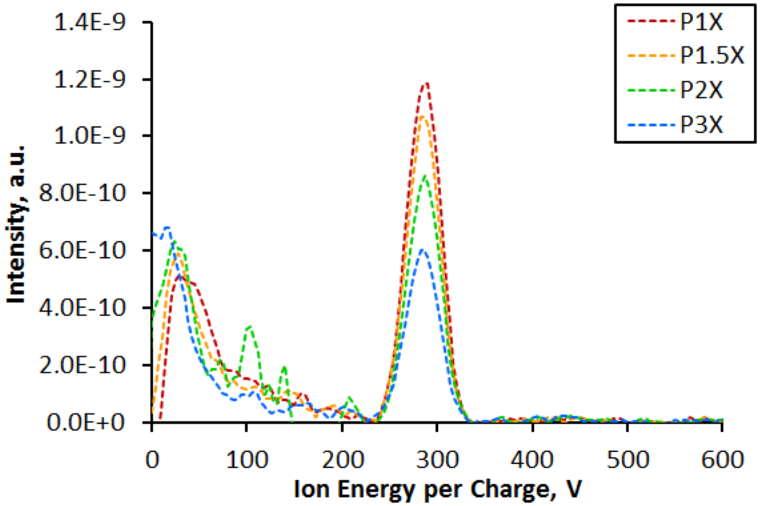
- During the design of the HERMeS thruster the team did not optimize the magnetic shielding- focus was to eliminate channel erosion as a life limiting mechanism for HERMeS

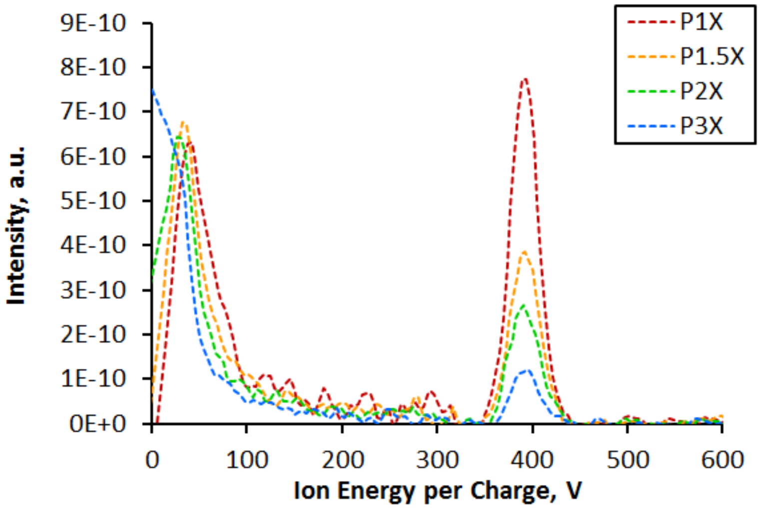
Motivation for Study

- Primary: Reduce the front pole cover erosion rates from the levels being currently measured while still maintaining low discharge channel erosion rates consistent with the required service life of the thruster;
- Primary: Explore reducing the plume divergence of the HERMeS thruster and reduce the high energy ion population that have been detected at large plume angles;
- Secondary: Explore improving the stability of the HERMeS thruster by reducing the oscillation levels during thruster operation;
- Secondary: Explore reducing the magnetic circuit components saturation at high magnetic field settings







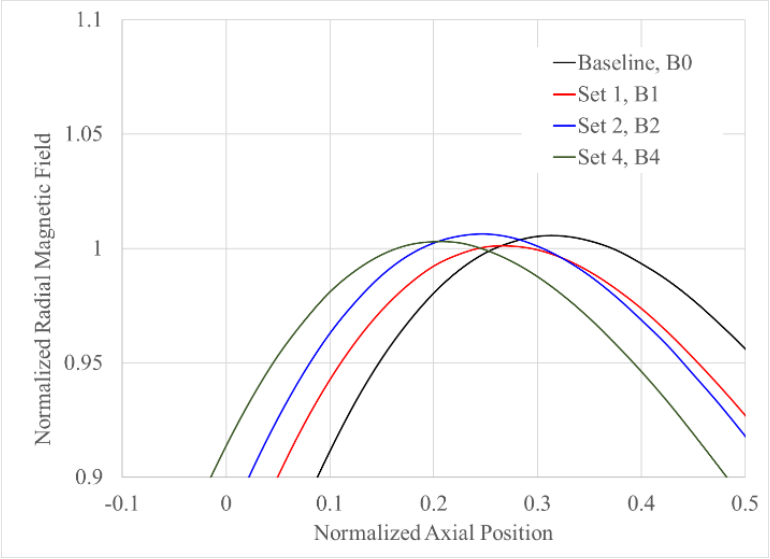


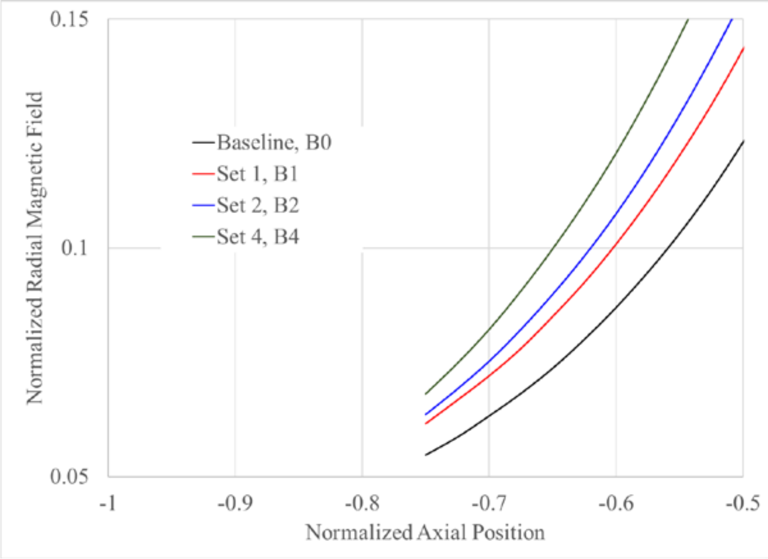
Characterize the erosion, performance, stability, and plume of the HERMeS thruster for alternate magnetic field topologies

Magnetic Field Optimization

Baseline Magnetic Field Topology

- B0 is the baseline TDU-1 (2&3) magnetic field topology
- B0 topology was implemented in TDU-1&2&3 and tests have shown that all three thrusters are magnetically shielded
- B1-B4 are the new topologies that are being investigated
- B1, B2, and B4 were built and mapped
- As we progress from B0 to B4 the magnetic field retracts upstream and the magnitude of the field at the anode increases slightly





	Normalized Location of Peak Br	Normalized Br, @ z/L = -0.75	Ratio of $Imag_{Bx}/Imag_{B0}$
Config B0, baseline	0.33	0.055	100%
Config B1, Set#1	0.28	0.062	93.0%
Config B2, Set#2	0.24	0.064	89.6%
Config B4, Set#4	0.20	0.068	83.7%

Modeling and Simulation with Hall2De

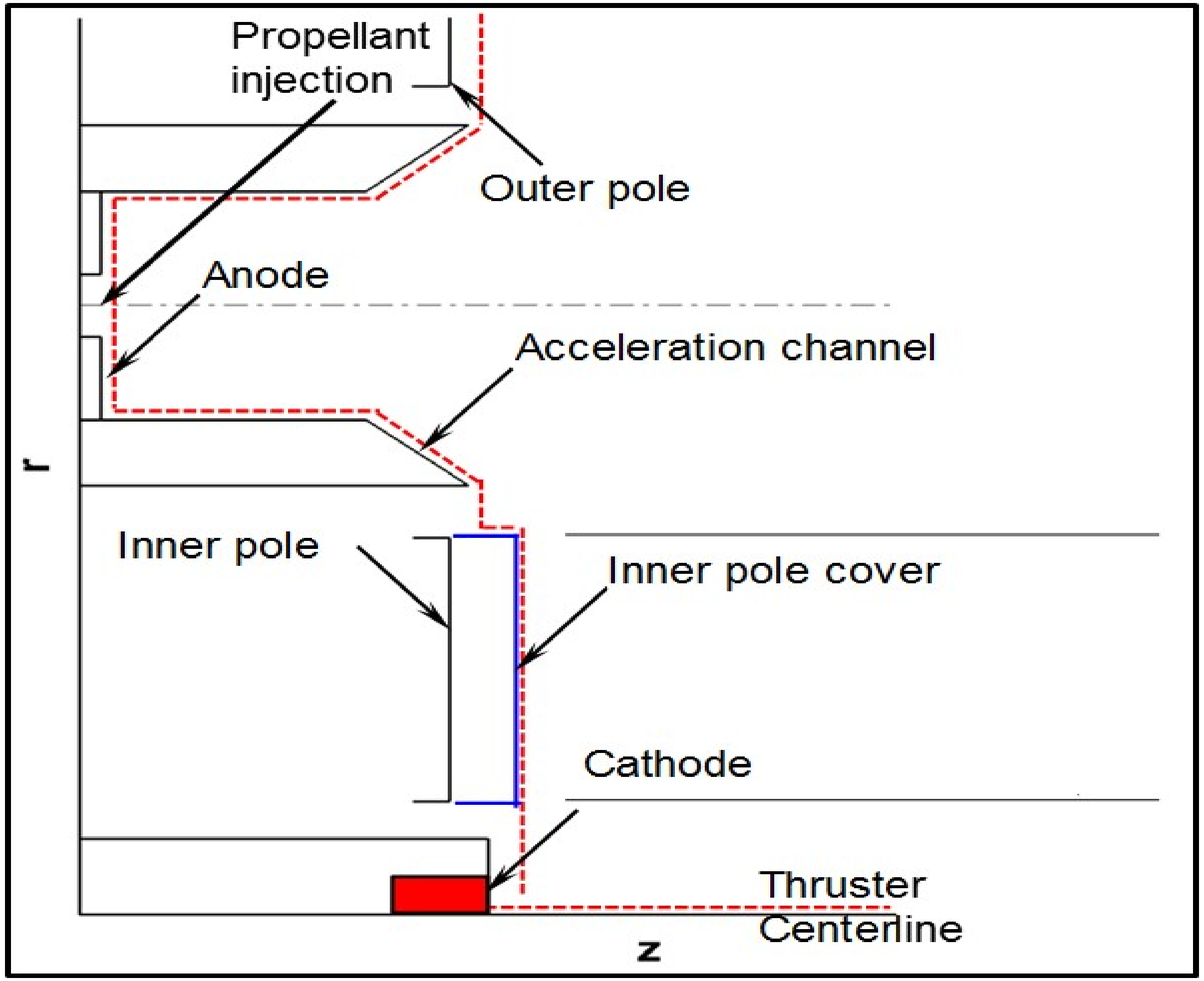
- The numerical simulations presented in this paper have been performed with the Hall2De code a 2-D axisymmetric computational solver of the conservation equations that govern the evolution of the partially ionized gas in Hall thrusters

- In Hall2De all governing equations are solved on a magnetic-field-aligned computational mesh (MFAM)

- Hall2De employs a multi-fluid algorithm and the code has been updated to allow for easier implementation of different electrical BCs

- Hall2De the MFAM spans a computational domain in r-z geometry that extends several times the thruster channel length in the axial direction

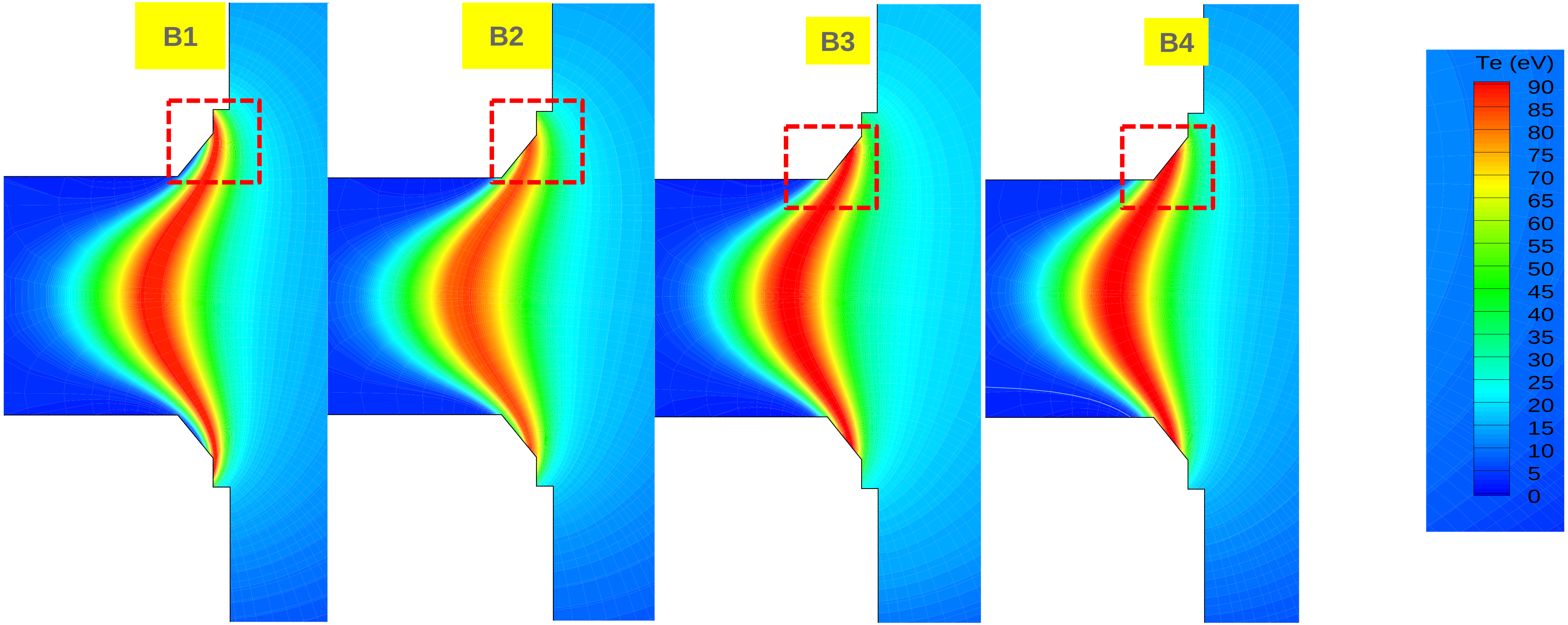
- The conservation equations solved by Hall2De are closed with boundary conditions (BC) at all surfaces.



Modeling and Simulation with Hall2De

Hall2De Electron Temperature Profiles at 600 V and 12.5 kW

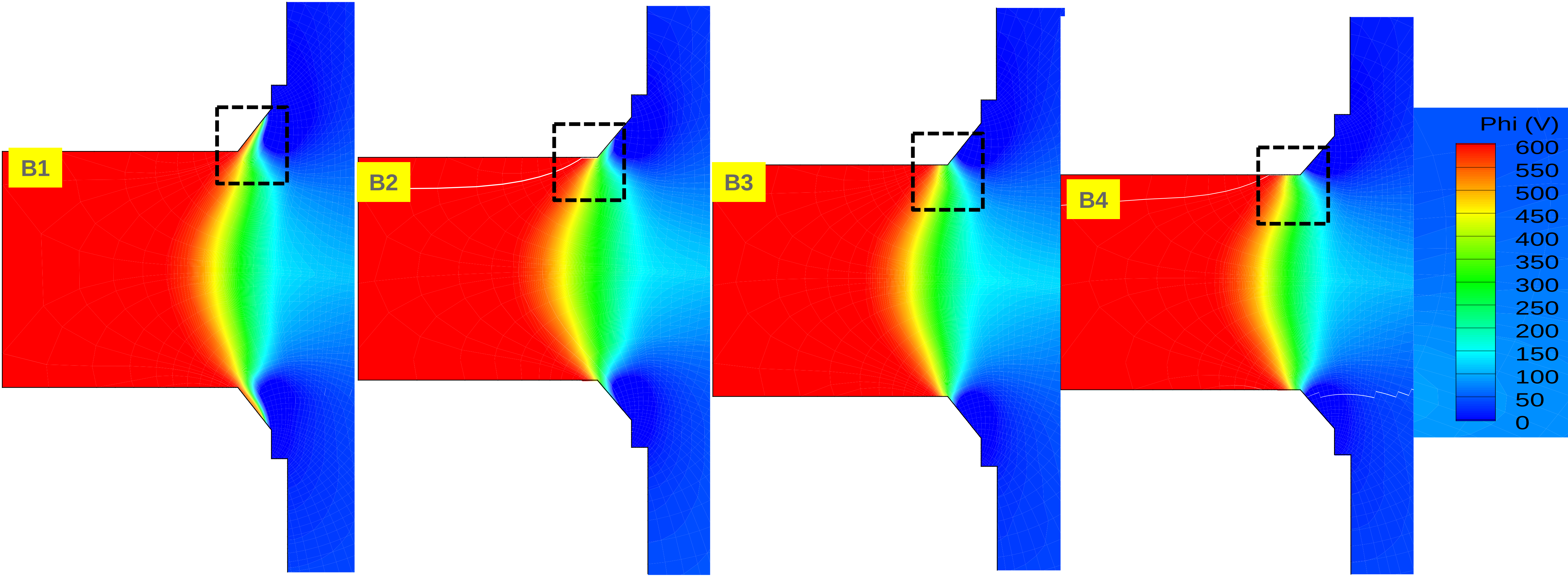
- **Numerical simulation performed for Configs B1-B4 for the thruster operating at 600V and 12.5 kW**
- **Time-averaged results for the electron temperature and plasma potential at 600 V and 20.8 A clearly illustrate how warmer electron temperatures are allowed along these boundaries as the MS topologies are retracted relative to B0.**



Modeling and Simulation with Hall2De

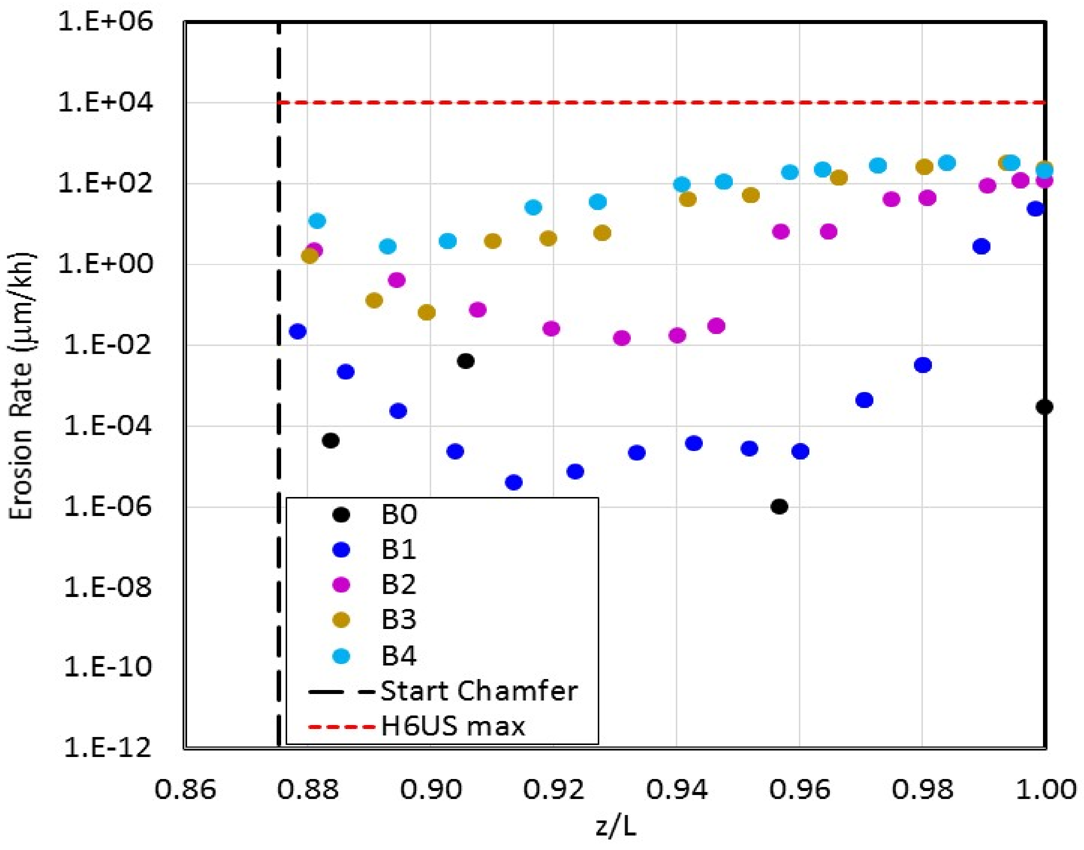
Hall2De Plasma Potential Profiles at 600 V and 12.5 kW

Time-averaged results for the electron temperature and plasma potential at 600 V and 20.8 A clearly illustrate how higher potential drops are allowed along these boundaries as the MS topologies are retracted relative to B0.



Hall2De Discharge Channel Computed Erosion Rates for B0-B4

- The erosion calculations used the same models for the sputtering yield as used previously and accounted for contributions from three charge states (Xe^{+}, Xe^{++} and Xe^{+++}) and three ion fluids
- The computed erosion along the inner channel wall for all MS increases in going from B0 to B4, with increasing values occurring further upstream from the channel exit along the chamfer. Similar results are found for the outer wall
- The computed erosion rate of B4 remains approximately two orders of magnitude below those measured in the H6US
- *Using the computed B4 erosion rate of ~100 μm/kh (B4) it would take approximately 38 khr for the channel to be completely eroded (> 50% above the 23 khr of operation of the AEPS propulsion system requirement)*
- The impact on the pole cover based on the current simulations is still under investigation since part of the physics that drive erosion along these boundaries remains elusive



Magnetic Field Topologies

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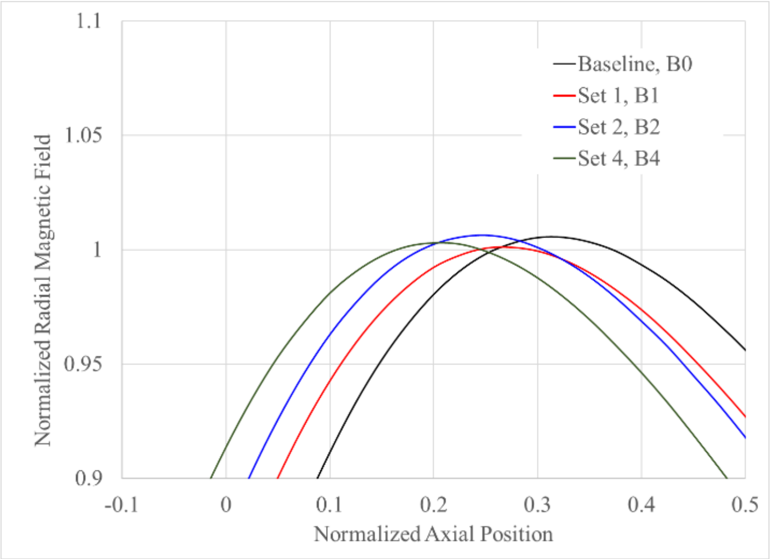

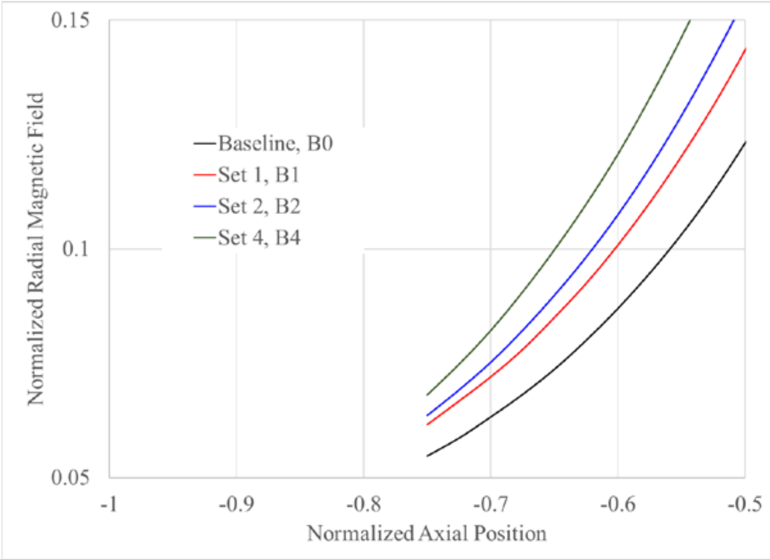

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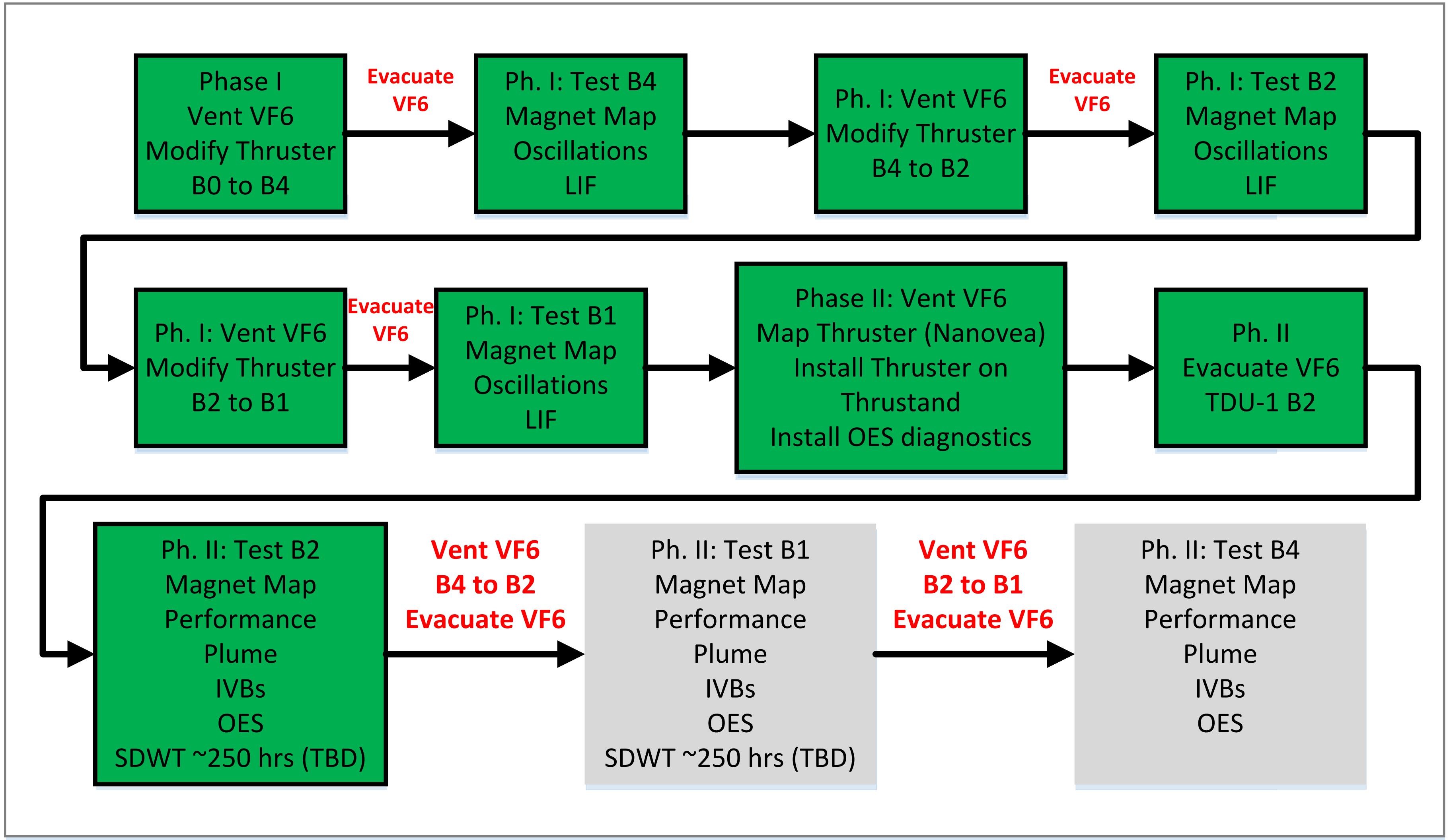
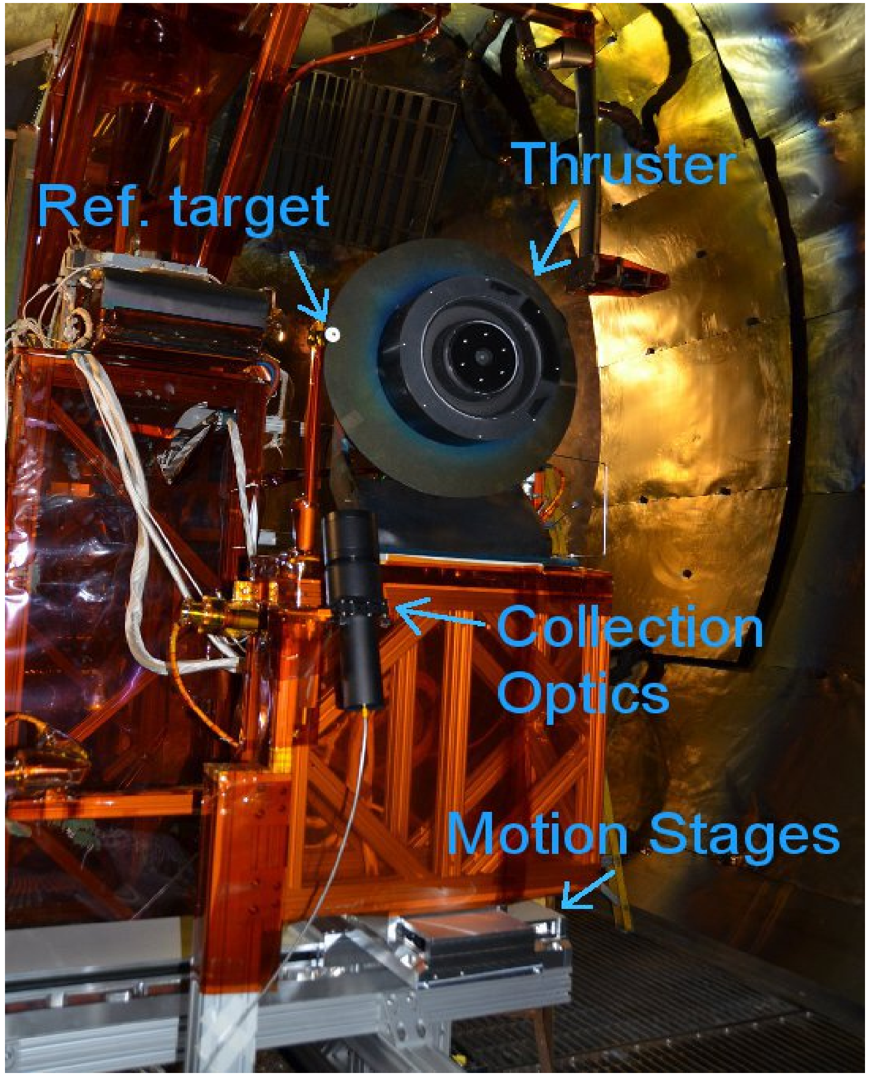
Test Plan



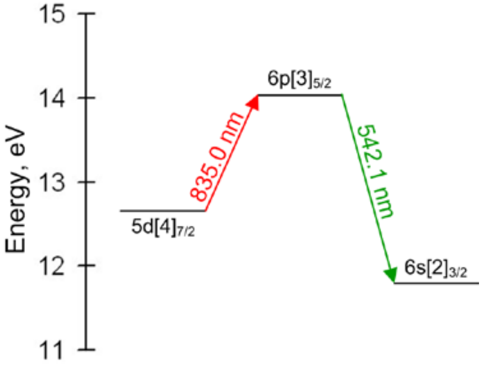
Phase I
Vent VF6
Modify Thruster
B0 to B4
Evacuate VF6
Ph. I: Test B4
Magnet Map
Oscillations
LIF
Ph. I: Vent VF6
Modify Thruster
B4 to B2
Evacuate VF6
Ph. I: Test B2
Magnet Map
Oscillations
LIF
Ph. I: Vent VF6
Modify Thruster
B2 to B1
Evacuate VF6
Ph. I: Test B1
Magnet Map
Oscillations
LIF
Phase II: Vent VF6
Map Thruster (Nanovea)
Install Thruster on Thrustand
Install OES diagnostics
Ph. II
Evacuate VF6
TDU-1 B2
Ph. II: Test B2
Magnet Map
Performance
Plume
IVBs
OES
SDWT ~250 hrs (TBD)
Vent VF6
B4 to B2
Evacuate VF6
Ph. II: Test B1
Magnet Map
Performance
Plume
IVBs
OES
SDWT ~250 hrs (TBD)
Vent VF6
B2 to B1
Evacuate VF6
Ph. II: Test B4
Magnet Map
Performance
Plume
IVBs
OES

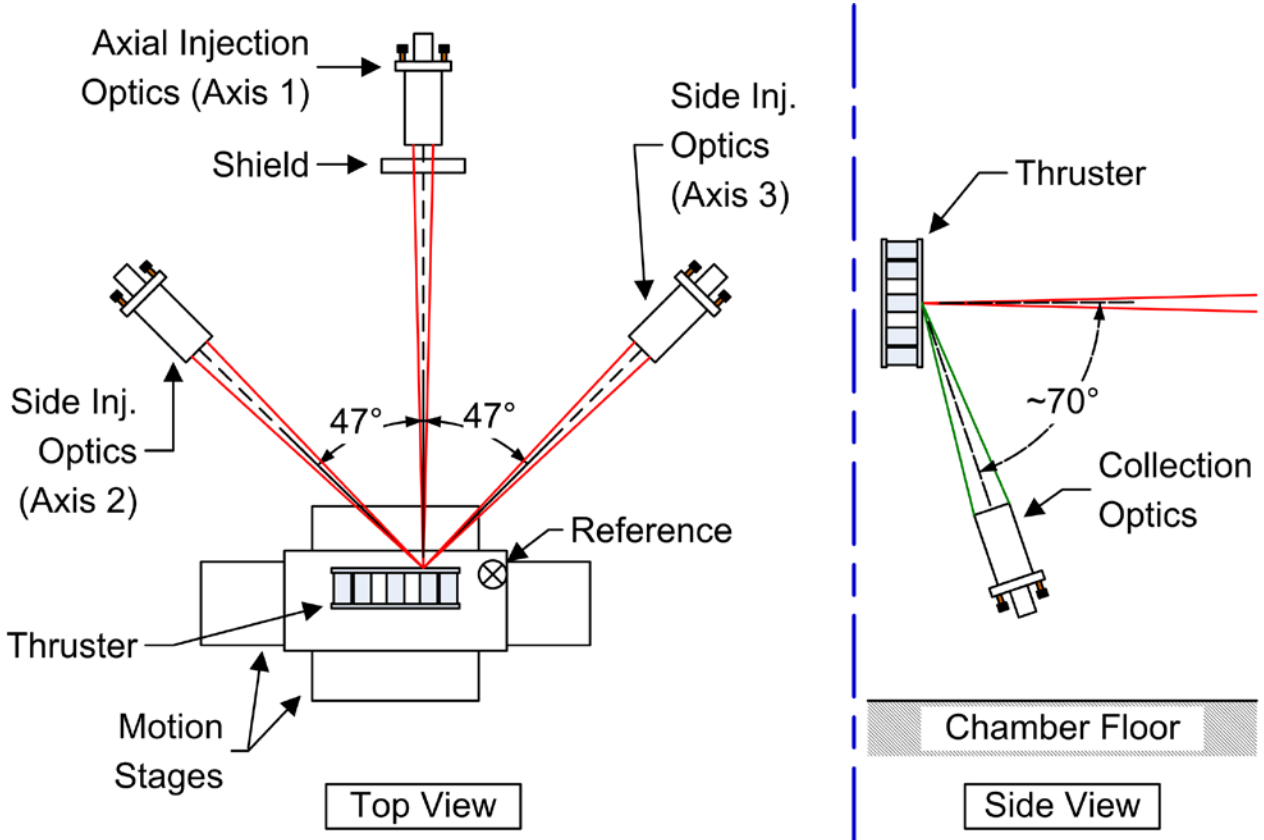
Experimental Apparatus

- **HERMeS TDU-1 Thruster**
  - **Magnetically shielded**
  - **Centrally mounted cathode**
  - **Heitage BN channel**
  - **Throttle range 0.6 kW- 12.5kW**
  - **Extensively tested in VF5 and VF6**
- **VF-6 vacuum facility**
  - **25 ft dia by 90 ft long**
  - **Walls covered with graphoil**
  - **Background pressure ~1.2e-5 Torr-Xe near thruster at 20.8 A**
- **Planned Diagnostics Include:**
  - **Laser induced fluorescence (LIF) will used to measure the ion velocities in the thruster discharge chamber, plume, and front pole cover regions;**
  - **Thrust Stand to measure the thrust magnitude produced by the thruster;**
  - **Plasma diagnostics array that includes a Faraday probe (FP), a Langmuir probe (LP), a retarding potential analyzer (RPA), and a Wien filter spectrometer (WFS). The plasma array provides measurement of the ion current density, local plasma potential, and charged species current fractions in the thruster's plume Refs. ;**
  - **Optical emission spectroscopy (OES) will be used to provide a qualitative assessment of the front pole cover erosion.**

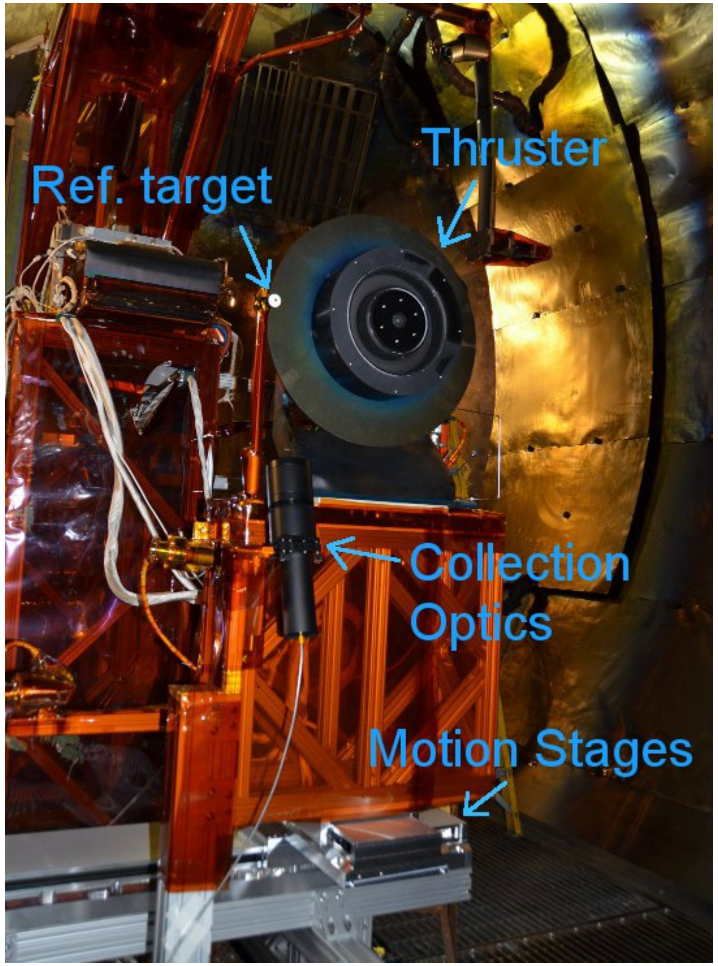


LIF Experimental Setup – Vacuum Side Optics





(a) (b)



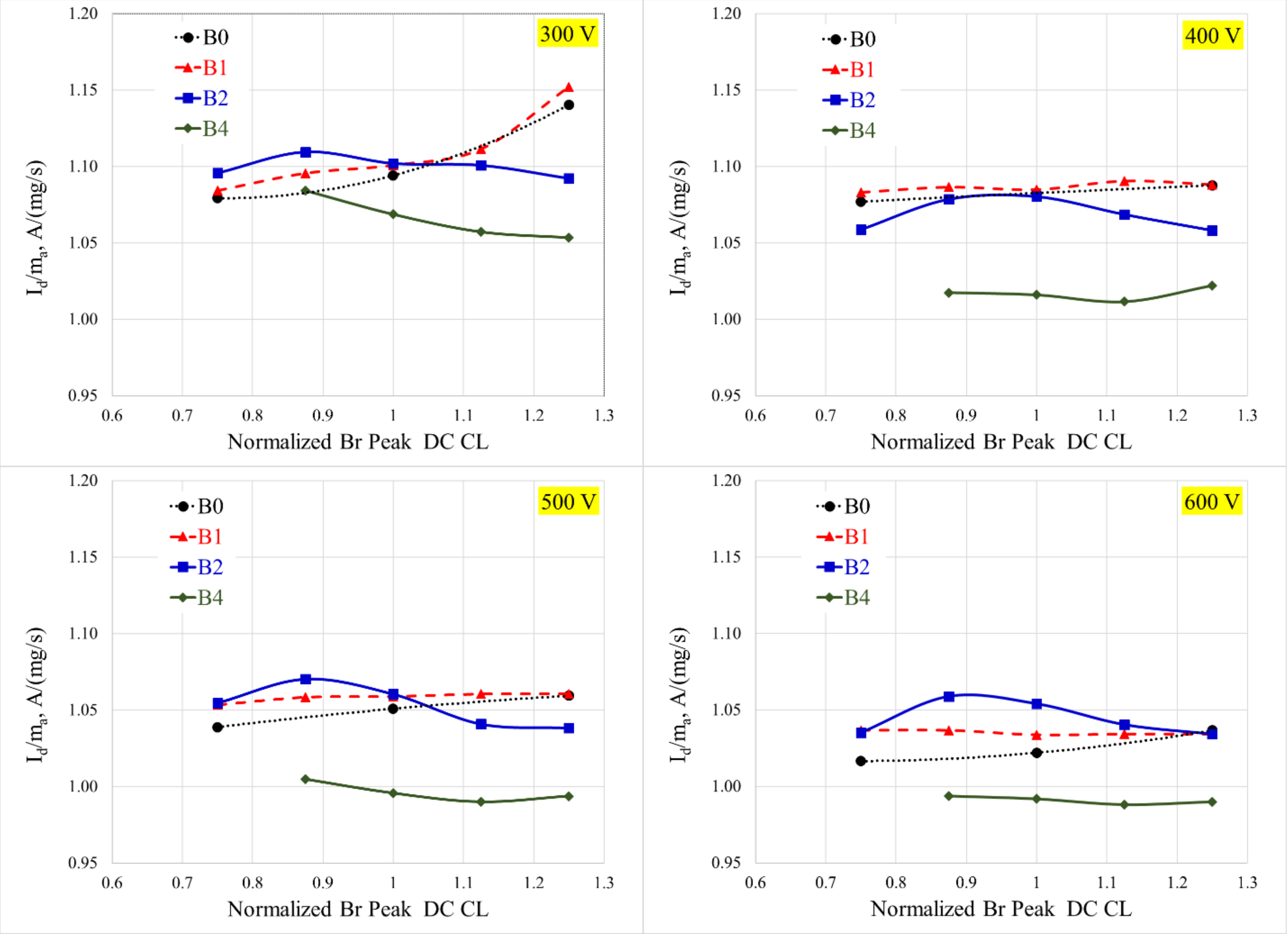
Huang et al., Ion Velocity in the Discharge Channel and Near-Field of the HERMeS Hall Thruster

AIAA-4723, Tue @ 17:00

Config B0, B1, B2, & B4 Id/ma Profiles @ 300- 600V 20.8A Operation

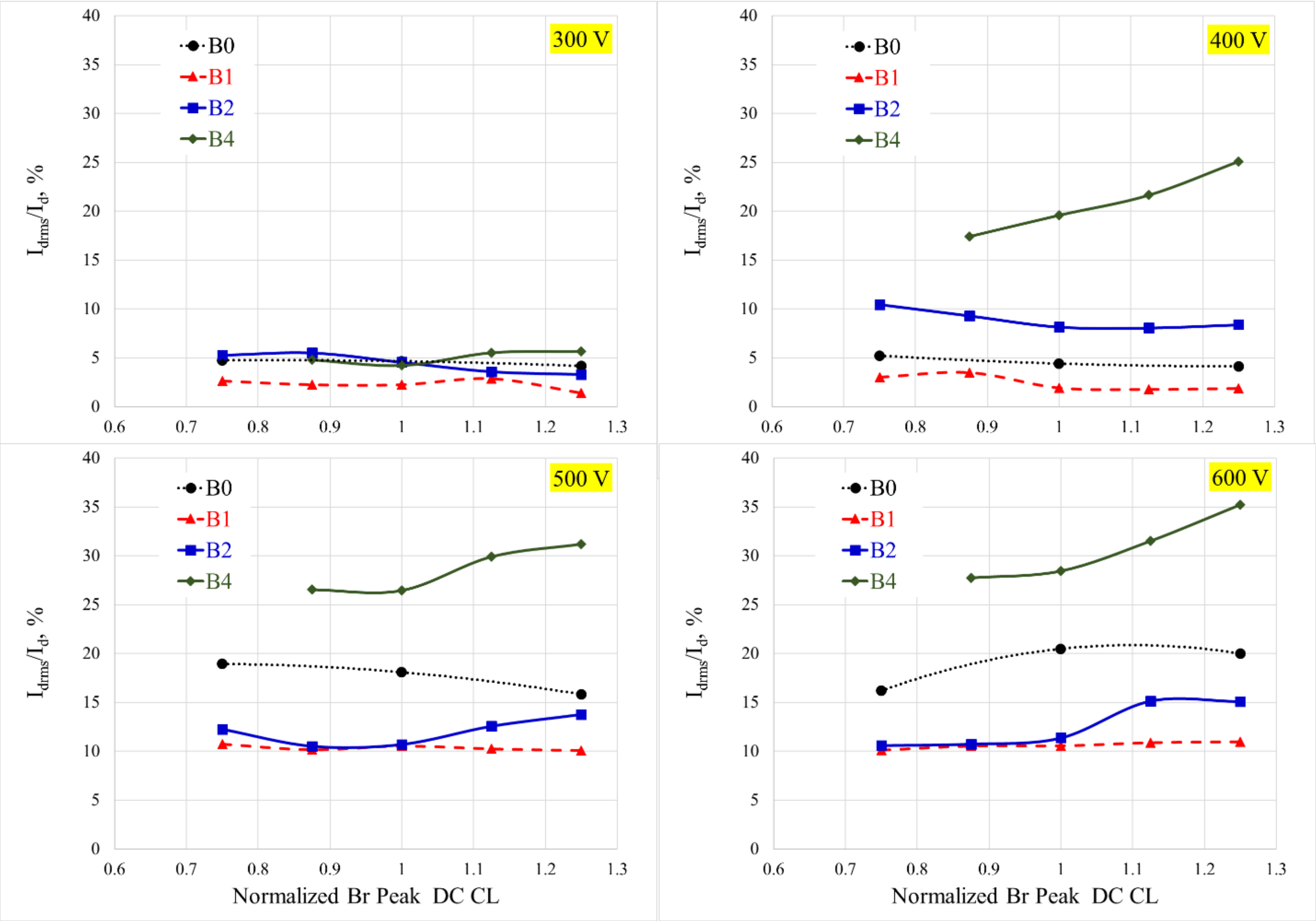
- The results show that for the most part the B1 and B2 profiles qualitatively followed that of B0.

- However, B4 showed a significant deviation from the B0 profile. This is an indication that a substantial field retraction results in changes to the nature and characteristics of the plasma discharge



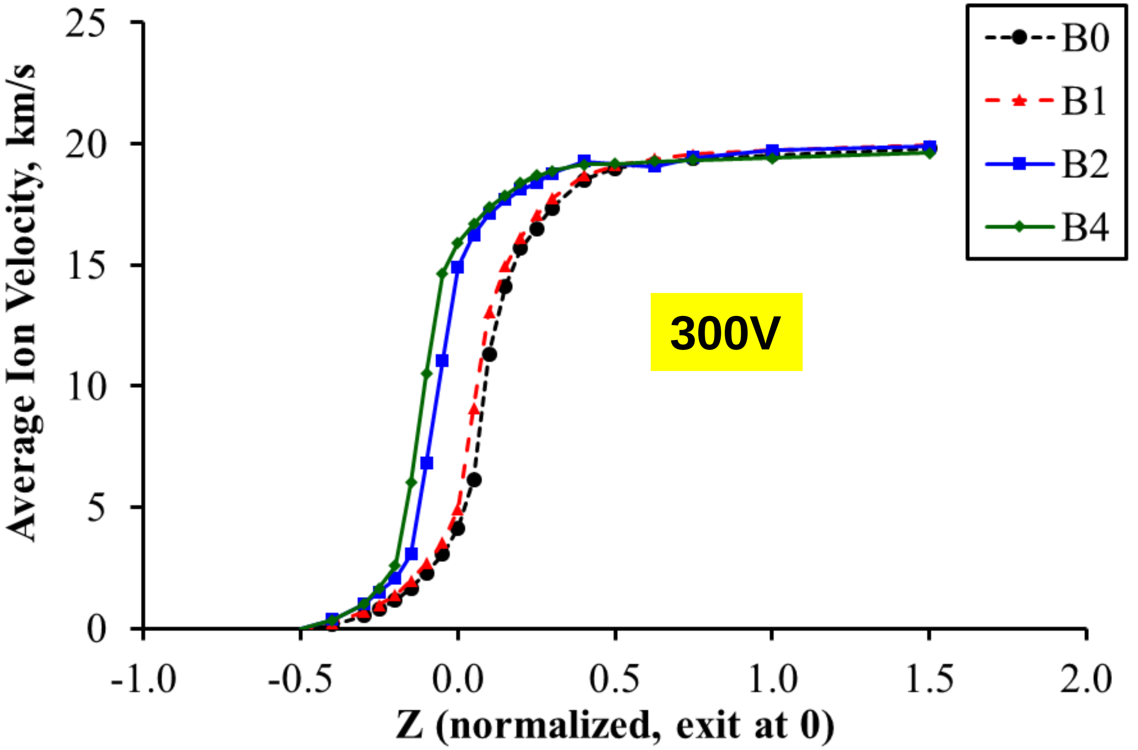
Config B0, B1, B2, & B4 Id_{rms}/Id Profiles @ 300- 600V 20.8A Operation

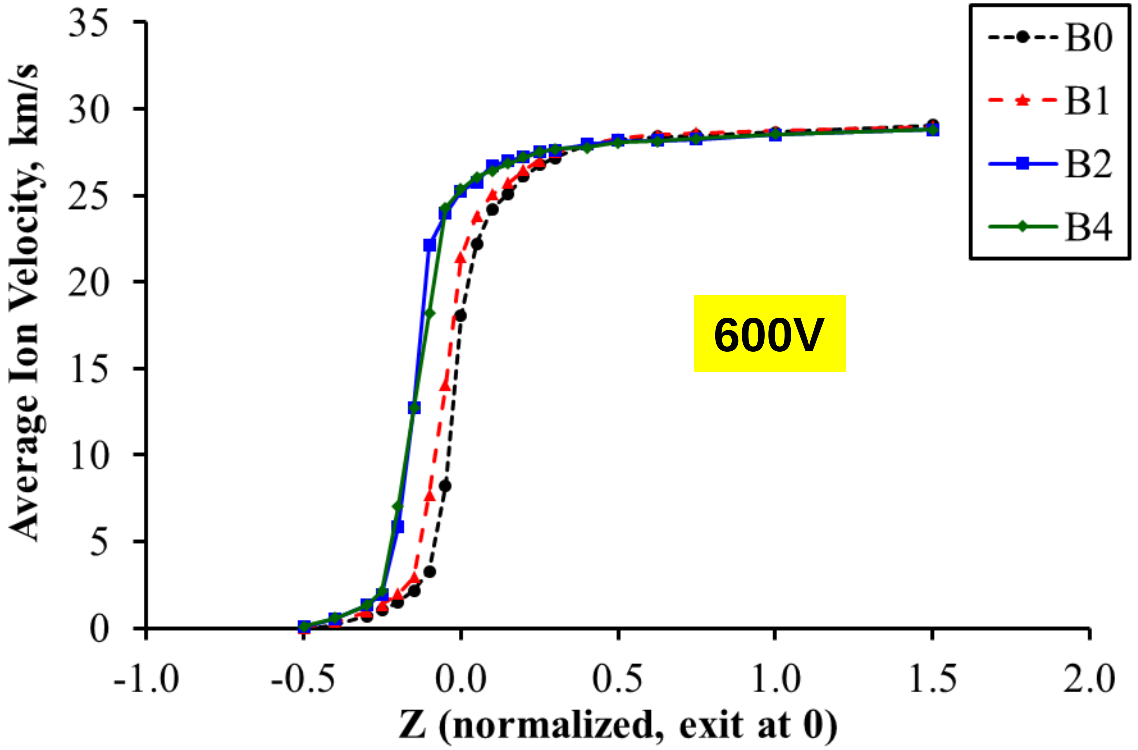
- Configuration B1 had the lowest oscillation levels for all thruster operating conditions
- Configuration B2 oscillation levels (compared to B0) were similar for 300 V operation, higher at 400 V, and were lower at 500 and 600 V
- Configuration B4, resulted in higher oscillation levels for all thruster operating conditions
- For configurations B1, B2, and B4 the thruster still transitioned to a high oscillatory mode between 400 and 500V which qualitatively similar to B0 operation



Ion Velocity Profiles along Discharge Channel CL for Configs B0, B1, B2, & B4 @ 300 & 600V

- LIF measurements performed: CL, 2D inside DC, & near front pole covers
- For 300 V operation, the B1 configuration shifts the acceleration zone slightly upstream when compared to the baseline configuration. The B2 and B4 configurations extend the acceleration zone upstream by 6 and 7 times as much as B1, respectively
- For 600 V operation, both B2 and B4 configurations extend the acceleration zone upstream by about 4 times as much as B1 relative to the baseline configuration

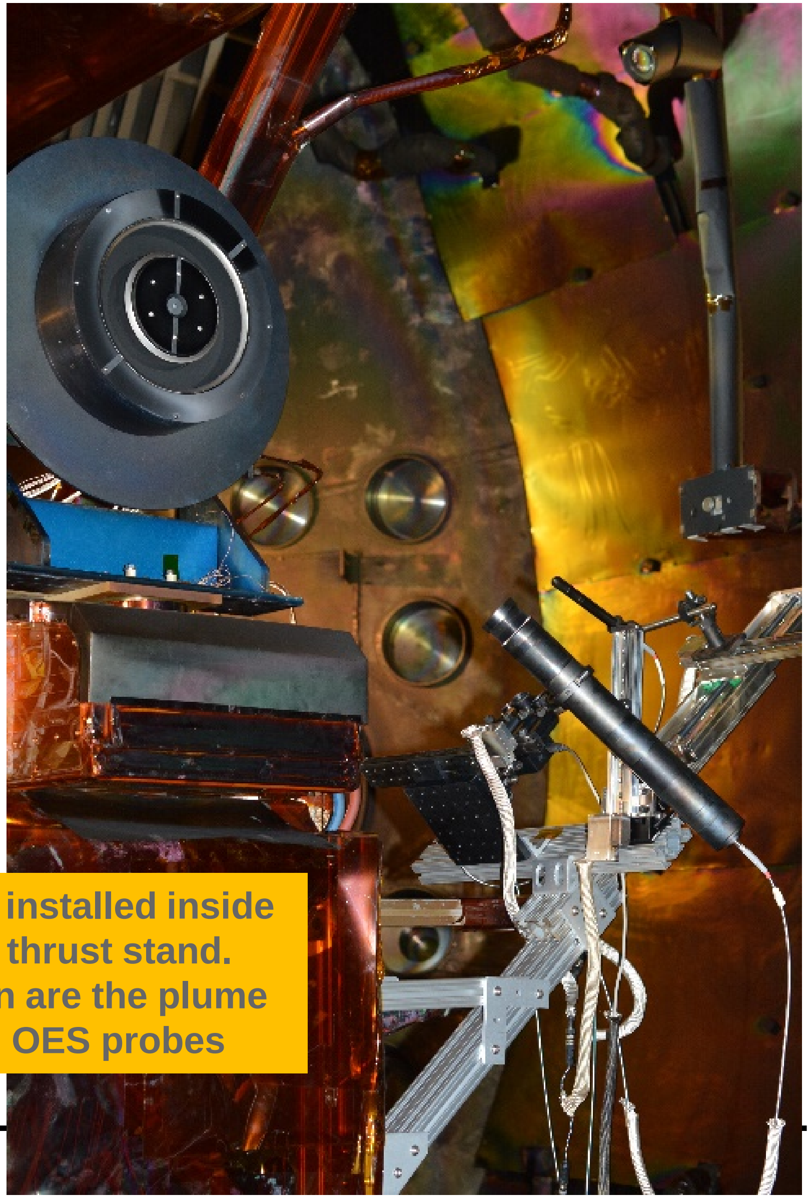




Phase II Testing Underway
Test of Config B2 Completed

- Tested Config B2
  - Pre test scans of polished IFPC & OFPC
  - Pre test scans of BN surface (360º)
  - Performance map
  - Plume maps (@ RFCs)
  - Magnet Map
  - Cathode flow fraction
  - Wear test for ~265 hrs @ 600V 12.5 kW
  - IVBs at 20.6 mg/s & CFF 5-9%
  - OES @ 300V/6.25kW & 600V/12.5kW
  - Post test scans of polished IFPC & OFPC
  - Post test scans of BN surface (360º)

- Testing of Config B1 will start July 16th
  - Pre test scans of polished IFPC & OFPC
  - Pre test scans of BN surface (360º)



TDU-1 installed inside VF6 thrust stand. Shown are the plume and OES probes

Conclusion

- Extensive testing of the HERMeS thrusters (TDU-1, TDU-2, and TDU-3) have found that the thruster design meets the 23 khr life service capability with a > 50% margin
  - HERMeS TDU thruster front pole cover erosion rates were higher than expected
- NASA GRC and JPL are investigating alternate thruster magnetic field topologies that still maintain discharge channel erosion rates consistent with the thruster’s throughput requirement, but reduce the inner front pole cover erosion rates
  - Four new magnetic field topologies were designed at NASA GRC and they were numerically modeled by NASA JPL using Hall2De
- Modeling of the four candidate magnetic field topologies found that, as expected, the discharge channel erosion rates in going from B0 to B4 rise, with increasing values occurring further upstream from the channel exit along the chamfer
- Phase I of the test campaign has been completed and results found that
  - Thruster operation during Configs B1 and B2 was qualitatively similar to Config B0
  - LIF ion velocimetry measurements during Configs B1-B4 tests indicated that the acceleration zone extended upstream due to retraction of the magnetic field but the shift magnitude was not one-to-one with magnetic field axial extraction
- Phase II testing is underway (Config B2 test completed)

Acknowledgements

The funding of the joint NASA GRC and JPL development of the HERMeS thruster and work performed by Aerojet Rocketdyne under the Advanced Electric Propulsion System (AEPS) contract by NASA's Space Technology Mission Directorate through the Solar Electric Propulsion Technology Demonstration Mission (SEP TDM) project is gratefully acknowledged.